



Sensations of temperature and humidity during alternative work/rest and the influence of underwear knit structure

RUTH NIELSEN†

IFK/National Institute of Occupational Health,
S-17184 Solna, Sweden

THOMAS L. ENDRUSICK

Military Ergonomics Division,
US Army Research Institute of Environmental Medicine,
Natick, MA 01760-5007, USA

Keywords: Subjective sensations; Exercise; Rest; Cold; Underwear; Thermoregulatory responses.

The purpose of this study was to evaluate the influence of alternate work/rest and knit structure of underwear on various subjective sensations of temperature and humidity. Underwear manufactured from 100% polypropylene fibres in five different knit structures (1-by-1 rib, fleece, fishnet, interlock, double-layer rib) were applied and tested as part of a prototype clothing system. Human testing was done on eight male subjects, and took place at $T_a = 5^\circ\text{C}$, $T_{dp} = -3.5^\circ\text{C}$ and $V_a = 0.32 \text{ m s}^{-1}$. The test comprised a twice-repeated bout of 40 min cycle exercise (56 W m^{-2} , $\dot{V}O_2 = 1.741 \text{ O}_2 \text{ min}^{-1} \sim 52 \pm 4.9\% \dot{V}O_2 \text{ max}$) followed by 20 min of rest (0 W m^{-2} , $0.351 \text{ O}_2 \text{ min}^{-1}$). Alternate work/rest had a significant influence on all temperature and humidity sensations of the body, of the skin-clothing interface, and of the environment. Knit structures of the underwear influenced sensations of humidity significantly, but not sensations of temperature. The various sensations of temperature correlated best with core temperature, whereas the sensations of humidity correlated with skin wettedness. Subjective sensations of wetness of the skin and of the clothing are recommended as a sensitive tool to discriminate between the thermal function of similar garments.

1. Introduction

In occupational as well as recreational outdoor activities, alternate work/rest is common. In autumn and winter, a varying activity level may easily result in periods of sweating and chilling. In these situations, thermoreceptors are of significance for autonomic temperature regulation, and for conscious sensation of the temperature of the body and of the actual environment. The sensitivity to thermal stimuli varies between the core and different body surface areas (Bleichert *et al.* 1973, Crawshaw *et al.* 1975). Humans have no humidity receptors, but in some way the wetness of the skin is also sensed, and can be related to the evaluation of comfort and discomfort (Winslow *et al.* 1937). Also, the clothing worn generates thermal and contact wearing sensations (Hollies *et al.* 1979, Gwosdow *et al.* 1986).

In nude people in a warm environment, a sense of pleasantness and comfort is associated with low values of skin wettedness (Winslow *et al.* 1937). When more than

[†]Present address: Ruth Nielsen, Laboratory of Heating & Air Conditioning (B.402), Technical University of Denmark, 2800 Lyngby, Denmark.

50-65° of the body surface is wet, it is experienced as discomfort (Gagge *et al.* 1969). In dressed people rather little moisture is probably required in the skin-clothing interface to introduce sensations of discomfort. Hollies (1965) reported that strong sensations of discomfort were noted when sweating occurred, and also during the periods of warming and chilling following the inception of sweating. After the addition of water to the shirt, he observed the same sensations as with sweating showing that water at the skin-fabric interface was involved. Also, the structure of the fabric perceived has been reported to change with moisture at the skin surface (Sullivan 1927, Gwosdow *et al.* 1986). To our knowledge, the significance of conscious thermal sensation from alternating warm and cold wetted clothing at the skin surface as a result of sweating during intermittent exercise in a cold environment has not been previously studied. How various fibre-type materials and knit constructions of the clothing layer next to the skin influences the microenvironment directly over the skin surface, and the sensory input from the skin under these thermal conditions is also unknown. Practical experience has demonstrated that cold, moist fabrics in contact with the body produce an unpleasant sensation, referred to as a 'chilling effect' or a 'clammy feel'.

The purpose of the present study was to investigate the development of various subjective temperature and humidity sensations of the body, of the skin-clothing interface, and of the environment in dressed subjects during alternate work/rest in an environment resulting in both periods of sweating and chilling. Further, we aimed to study the significance of the knit structure in underwear on the subjective sensations during the course of the test, and whether there was any correlation between subjective sensations and physiological/physical observations.

2. Methods

2.1. Subjects

Eight healthy males volunteered for the present series of experiments. Before any testing, the subjects were informed about the purpose of the study, any known risks, and their right to terminate participation without penalty. They expressed understanding by signing a statement of informed consent. None of the subjects did more than two test sessions per week. They had an average (\pm s.d.) age of 23 ± 4.9 years, weight of 74 ± 11.6 kg, height of 177 ± 4.7 cm, DuBois surface area (A_{Du}) of $1.91 \pm 0.146 \text{ m}^2$ and maximal oxygen consumption of $3.34 \pm 0.6441 \text{ O}_2 \text{ min}^{-1}$.

2.2. Garment description

The clothing system was comprised of a two-piece long-sleeved/long-legged underwear ensemble, a Battle Dress Uniform (BDU) shirt and trousers (50% cotton/50% nylon), woollen socks, gym shoes, and woollen gloves. Underwear manufactured from 100% polypropylene fibres in five different knit structures (1-by-1 rib (K1), fleece (K2), fishnet (K3), interlock (K4), double-layer rib (K5)) were worn. Insulation values of all five clothing systems and all five underwear ensembles were measured on a thermal manikin (Madsen 1971) (see table 1). Each subject had his own separate clothing system. Before any testing was done on humans, all underwear and the rest of the clothing system were laundered and air-dried five times without the use of any detergent. This was done to remove any excess finishing chemicals in the textiles. For each subject, the order in which the clothing systems were tested was randomized.

Table 1. Physical characteristics of the textiles and the garments applied (ASTM D1518-77, ASTM D1774-64, DIN 54101). The textile samples of underwear material were measured alone, and with the BDU-textile placed on top. The underwear ensembles were measured on the thermal manikin, and also the total clothing ensemble tested on human comprising underwear, battle dress uniform (BDU), socks, shoes and gloves.

	Underwear knit structure					
	1-by-1 rib K1	Fleece K2	Fishnet K3	Interlock K4	2-layer K5	BDU
Textile samples						
Fabric thickness (mm) with BDU-textile on top	0.84 1.33	1.65 2.06	1.04 1.40	1.04 1.43	0.81 1.30	0.58
Thermal resistance* with BDU-textile on top ($\text{m}^2 \cdot \text{K} \cdot \text{W}^{-1}$)	0.156 0.165	0.193 0.208	0.139 0.166	0.148 0.160	0.147 0.164	0.121
Water vapour resistance** with BDU-textile on top ($\text{m}^2 \cdot \text{Pa} \cdot \text{W}^{-1}$)	15.0 21.7	19.5 23.8	17.1 20.2	15.4 23.8	16.0 23.4	12.5
Total thermal resistance (R_{tot})*** of clothing on thermal manikin ($\text{m}^2 \cdot \text{K} \cdot \text{W}^{-1}$)						
Underwear ensemble only	0.136	0.164	0.140	0.144	0.144	
Total clothing system	0.243	0.268	0.256	0.248	0.250	

* Includes thermal resistance of air over the flat plate: $0.106 \text{ m}^2 \cdot \text{K} \cdot \text{W}^{-1}$.

** Includes water vapour resistance of air over the flat plate: $8.8 \text{ m}^2 \cdot \text{Pa} \cdot \text{W}^{-1}$.

*** Includes thermal resistance of air around the thermal manikin (R_a): $0.104 \text{ m}^2 \cdot \text{K} \cdot \text{W}^{-1}$.

2.3. Experimental protocol

Conditions were designed to mimic real-life situations where sweating and after-exercise chill would develop while wearing this type of clothing. Testing occurred in a climatic chamber at an air temperature ($T_a = T_{\text{globe}}$) of $5.0 \pm 0.52^\circ\text{C}$, a dew point temperature of $-3.5 \pm 0.31^\circ\text{C}$ ($\sim 54\%$ relative humidity), and an air velocity of 0.32 m s^{-1} . The air flow was created by large fans and directed towards the front of the subject.

To standardize the initial heat content of the five clothing systems and thus eliminate this as a factor of variation for the heat exchange in the body clothing environment during the experiment, a rigid procedure was followed. The clothing was stored in the antechamber at least two hours before the experimental procedure began ($T_a = 29^\circ\text{C}$ and $rh = 20\% \sim 6.0 \text{ kPa}$). The standardized dressing procedure of the subject also took place in this antechamber. Each subject reported to the laboratory at the same time of the day for all experiments to avoid any circadian variation in body temperature. After arrival he was weighed in the nude and then instrumented with chest electrodes for heart rate (HR), thermocouples for esophageal and skin temperatures and dew point sensors on the skin, and approximately 10 min later he began the 2 h test. The test comprised a twice-repeated bout of 40 min of cycle exercise (60 rpm; $1.8 \pm 0.37 \text{ kp}$) followed by 20 min of rest on the ergometer (EX1, RE1, EX2, and RE2). Each subject always exercised at the same exercise intensity (an average of $56 \pm 9.01 \text{ W} \cdot \text{m}^{-2}$) that had been chosen so it would approximate 55% of his $\dot{V}\text{O}_2 \text{ max}$. The oxygen consumption measured during exercise was at average $1.74 \pm 0.3451 \text{ O}_2 \text{ min}^{-1}$ ($52 \pm 4.9\% \dot{V}\text{O}_2 \text{ max}$) and during rest $0.35 \pm 0.0851 \text{ O}_2 \text{ min}^{-1}$.

Esophageal, skin and air temperatures, as well as dew point temperatures at the skin and in the ambient air were monitored every minute during the test and stored for analysis. Body weight was sampled every 20 s from a Potter bed balance and HR was recorded every 10 min. $\dot{V}O_2$ was measured during the last 5 min of the first exercise and rest period, respectively. Two minutes after cessation of the test the subject left the test chamber and undressed immediately in the antechamber.

2.4. Subjective reactions

Psychophysical rating ballots were developed to obtain information about local and overall thermal sensation (Gagge *et al.* 1969), degree of shivering and sweating (modified from Nielsen *et al.* 1987), sensation of skin (modified from Umbach 1982) and clothing wetness, clothing comfort and ambient temperature preference (Nielsen *et al.* 1987) (figure 1, part I). The rating scales and the various sensations were discussed with the subject in advance of the first experiment. These scales were presented to the subject every 10 min during the experiment. After each experiment the subject was asked to give a more general evaluation of the properties of the clothing system worn (figure 1, part II).

2.5. Physiological variables

The methods used to measure oxygen uptake, esophageal temperature, skin temperature, dew point temperatures near the skin, evaporative heat loss, non-evaporated and total sweat loss are described in detail elsewhere (Nielsen and Endrusick 1989). Mean skin temperature (\bar{T}_{sk}) was calculated as an area-weighted average of measurements from nine different skin sites using the formula (modified from Gagge and Nishi 1977):

$$\begin{aligned}\bar{T}_{sk} = & 0.05T_{hand} + 0.07(T_{forearm} + T_{upperarm} + T_{head}) + 0.20T_{calf} + 0.19T_{thigh} \\ & + 0.175(T_{chest} + (T_{upperback} + T_{lowerback})/2) \quad (\text{C})\end{aligned}$$

Mean body temperature was calculated as (Hardy and DuBois 1938):

$$\bar{T}_b = 0.8T_{es} + 0.2\bar{T}_{sk} \quad (\text{C})$$

Local skin wettedness (w) on the back, chest and thigh was calculated as:

$$w = (P_{sk} - P_w)/(P_{s,sk} - P_w)$$

where P_{sk} is the vapour pressure at the skin surface obtained from the dew point sensor, $P_{s,sk}$ is the saturated vapour pressure at the local skin temperature and P_w is ambient water vapour pressure (Berglund *et al.* 1983). An average skin wettedness for thigh and torso area was estimated using the actual local skin surface area's fraction of the total body surface area:

$$w = (0.175w_{chest} + 0.175w_{back} + 0.190w_{leg})/0.54$$

2.6. Statistical analysis

A paired *t*-test was used to test whether there was any difference in subjective ratings between the first and the second test period. Repeated-measures analysis of variance (ANOVA) was used to determine whether the factor 'knit structure' had any significant effect on subjective sensations during the course of the test. In the event that ANOVA revealed significant main effect, Tukey's critical difference was calculated and used to locate significant difference between means. All differences reported are significant at

PART I		PART II	
<p>How is the overall thermal state of your 1) body ?, 2) feet ?, 3) hands ?</p> <p>1 very cold 2 cold 3 cool 4 slightly cool 5 neutral 6 slightly warm 7 warm 8 hot 9 very hot</p>		<p>How does the clothing feel ?</p> <p>1 dry 2 slightly damp 3 damp 4 wet</p> <p>1 cold 2 slightly cold 3 neutral 4 slightly warm 5 warm</p> <p>1 smooth 2 slightly rough/scratchy 3 rough/scratchy 4 very rough/scratchy</p> <p>Are you ?</p> <p>1 heavily shivering 2 moderately shivering 3 slightly shivering 4 not at all shiv./sweat? 5 slightly sweating 6 moderately sweating 7 heavily sweating</p> <p>How does your skin feel ?</p> <p>1 more dry than normal 2 normal dryness 3 Chest and back slightly wet 4 Chest and back wet 5 body wet 6 body wet: clothing sticks on the skin 7 sweat runs somewhere off 8 sweat runs off many places</p>	
		<p>How do you evaluate the performance of your clothing ensemble during the test ?</p> <p>1 comfortable 2 slightly uncomfortable 3 uncomfortable 4 very uncomfortable</p> <p>How did the garment fit ?</p> <p>1 very snug 2 snug 3 slightly loose 4 loose</p> <p>Did the garment cling to your body ?</p> <p>1 not at all 2 some 3 a lot</p> <p>How would you prefer the ambient air temperature ?</p> <p>1 much cooler 2 slightly cooler 3 no change 4 slightly warmer 5 much warmer</p>	

Figure 1. Rating ballots.

the $p < 0.05$ level. SAS (1985) was used to do transformations of the ballot axes, correlations and linear regressions between pairs of selected variables, and the SAS stepwise procedure to include several selected variables in a linear model.

3. Results

3.1. Subjective ratings during alternating work/rest

Average values of the subjective ratings for each clothing system are presented in figure 2. Alternating work/rest had a significant influence on all subjective ratings. The rating of the thermal sensation from the whole body changed during the course of the exercise reaching an average level between 'slightly warm' and 'warm' after 30 min. In the beginning of the rest period the thermal sensation changed abruptly, and after 10 min was graded between 'neutral' and 'slightly cool', while after 20 min of rest it was graded even cooler. There was no difference between the ratings in EX1-RE1 and in EX2-RE2. The hands were experienced as 'slightly warm' to 'warm' at the end of both exercise periods, 'neutral' after 10 min of rest, and between 'neutral' and 'slightly cool' at the end of the rest periods. The ratings in EX1-RE1 and EX2-RE2 only differed significantly after 10 min of rest, when the hands were sensed colder in RE2 than RE1. The feet were judged between 'neutral' and 'slightly cool' in the beginning of EX1; however, over the course of the exercise the judgement changed to between 'neutral' and 'slightly warm'. During RE1 the rating of the feet changed to 'slightly cool'. In EX2 the judgement increased again to 'neutral' and during RE2 to 'slightly cool' to 'cool'. All ratings in EX2-RE2 were lower compared to the same time in EX1-RE1 ($p < 0.05$; $n = 40$) except 9 min vs 69 min.

Sensation of sweating was at average judged between 'slightly sweating' and 'moderately sweating' at the end of both exercise periods. No difference was visible in the course of this sensation in the two periods, except when comparing the beginning of the two exercise periods (9 min vs 69 min), where the sensation of sweating was higher in EX2 compared to EX1 ($p < 0.05$). After 10 min of rest, sweating was on the average no longer experienced, and at the end of the rest periods shivering was reported from some subjects.

Sensation of wetness of the skin changed from normal dryness to 'chest and back wet', 'body wet' to 'clothing sticks to the skin' at the end of both exercise periods. The sensation of wetness decreased during the rest periods, but after 20 min of rest chest and back was still rated between 'slightly wet' and 'wet'. The wetness tended to be rated higher in EX2 compared to EX1 ($p < 0.1$), but the difference was only significant when comparing the beginning of the two exercise periods (9 min vs 69 min).

Sensation of wetness of the clothing changed from 'dry' to between 'slightly damp' and 'wet' after 40 min of exercise. During rest the clothing was still being rated 'slightly damp' to 'damp'. The clothing was rated significantly more damp in the second exercise period compared to the first ($p < 0.05$; 9 min vs 69 min, 19 min vs 79 min, 29 min vs 89 min).

The sensation of the temperature of the clothing changed slightly during the exercise and was 'neutral' to 'slightly warm' at the end of the exercise. At rest the clothing was rated 'neutral' to 'slightly cold'. There was no difference between the ratings in the two periods, except at the end of the 40 min of exercise when the clothing was rated warmer in EX1 ($p < 0.05$).

During exercise the subjects expressed a preference for a slightly lower ambient temperature, whereas at rest they would have preferred a slightly higher air

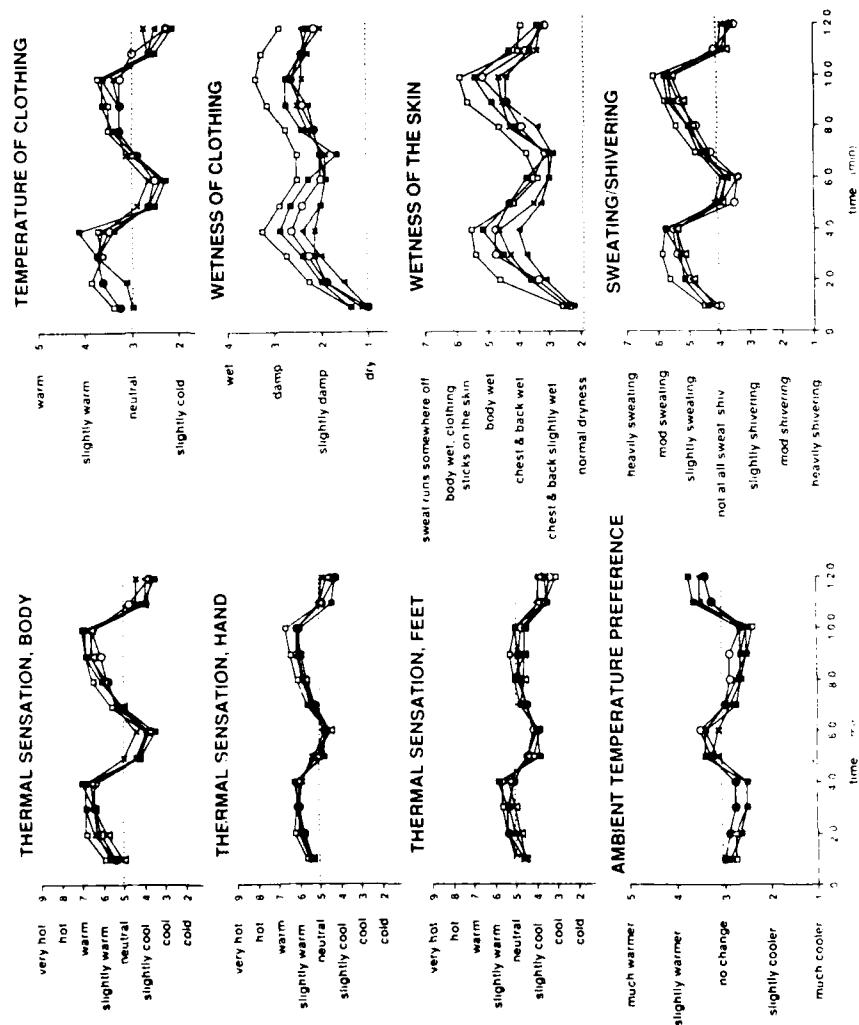


Figure 2. Time progression of the subjective ratings ($n=8$). (K1○, K2△, K3×, K4†, K5■).

temperature. There was a slightly higher rating during RE2 compared to RE1, being significant for 49 min vs 109 min ($p < 0.05$).

The actual sensation of the underwear against the skin was judged as smooth by almost all subjects, and this judgement did not vary over the course of the test. After the test nearly all subjects evaluated the clothing ensemble to have been comfortable during the test, to have had a 'snug' or 'slightly loose' fit, and to have clung somewhat to the body.

3.2. Effect of knit structure on subjective reactions

The sensation of wetness of the clothing was the subjective experience most significantly influenced by the knit structure of the underwear worn. After 10 min of exercise K2 and K5 were reported to be more damp than K1 and K4 ($p < 0.05$). Throughout the test K2 continued to be rated more damp than some of the other knit structures under study (20 min: K2 > K4; 40 min: K2 > K3, K4; 50 min: K2 > K3, K4; 90 min: K2 > K4; 100 min: K2 > K1, K3, K4; 110 min: K2 > K4). Four of the five knit structures (K1, K2, K3, K4) were sensed more damp at 69 min compared to 9 min ($p < 0.05$), and for K2 and K4 this difference persisted even at 19 min vs 79 min.

Sensed wetness of the skin tended to be rated highest with K2; however, there was only a significant effect of knit structure after 20 and 30 min in both exercise periods (K2 > K4). For both K2 and K4 wetness of the skin was rated significantly higher in the beginning of EX2 compared to EX1 (9 min vs 69 min, and for K2 also 19 min vs 79 min). Sensed temperature of the clothing also tended to be higher and warmer with K2 than K3 and K4, and sensation of sweating during work tended to be rated higher wearing K2 compared to the other clothing systems; however, the effect of knit structure was only significant at 19 min. No main effect of the knit structure of the underwear could be detected at any single time on the grading of thermal sensation of the whole body, of thermal sensations of the hands and the feet, or on the ambient temperature preference.

The actual sensation of the underwear against the skin was not influenced by the knit structure. The answers to questions asked after the experiment about the performance of the garment did not show any variation with knit structure.

3.3. Thermoregulatory responses

Alternating work rest had a significant influence on the thermoregulatory responses (figure 3) (described in detail in Nielsen and Endrusick 1989). Knit structure of the underwear in the prototype clothing ensemble had no influence on core temperature, but had a significantly large influence on the thermoregulatory responses at the skin during the intermittent exercise. Differences were found in mean skin temperature, body temperature, local and average skin wettedness, and non-evaporated and evaporated sweat.

3.4. Relationship between subjective ratings and physiological reactions

Subjective ratings were compared with selected physiological variables that possibly could have affected the grading. The sensation of the wetness of the clothing correlated well with average skin wettedness ($r = 0.62$). The sensation of wetness of the clothing at the end of the test was well correlated with the amount of non-evaporated sweat, i.e., sweat accumulated in the clothing ($r = 0.63$).

The sensation of skin wetness also correlated well with the measured average skin wettedness ($r = 0.63$), and this relationship was significant at each time (9, 19, ..., 119 min). Transforming the rating scale on skin wetness into a logarithmic

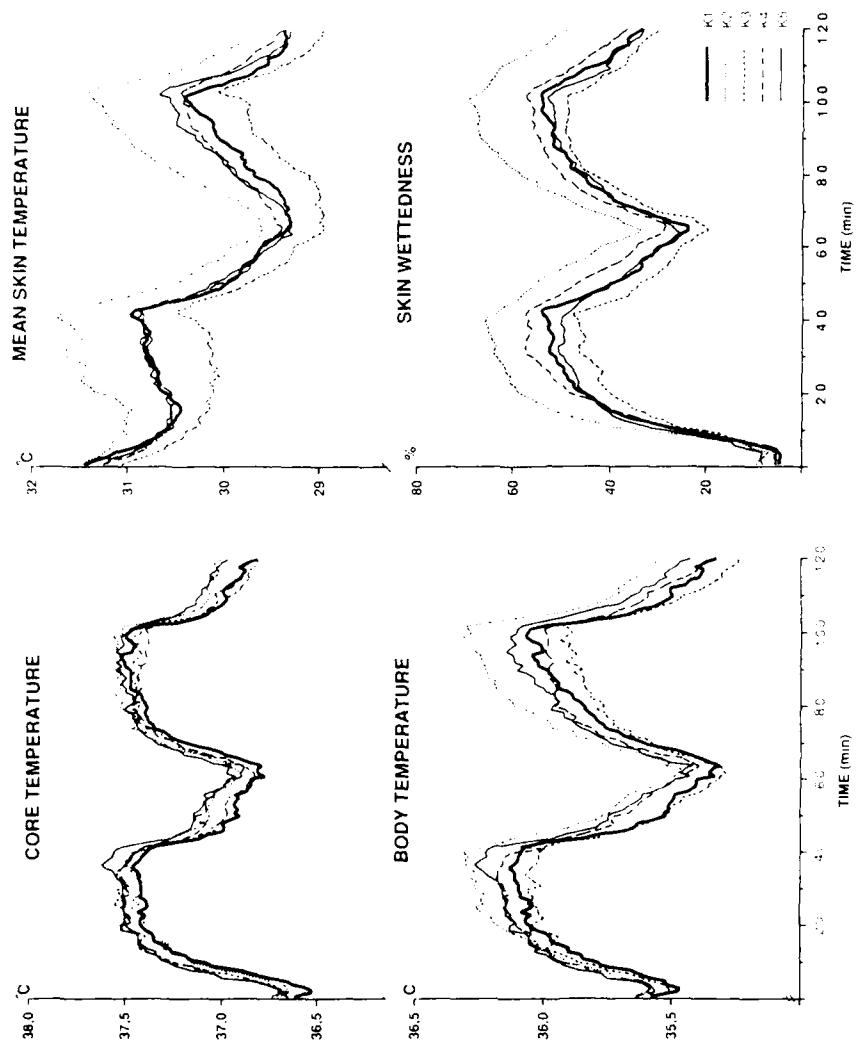


Figure 3. Time progression of esophageal, mean skin temperature, body temperature and average skin wettedness ($n=8$).

scale before the correlation was done showed no improvement in the correlation coefficient ($r = 0.66$). Adding skin or core temperature to the model did not provide a better correlation. Measured skin wettedness at the chest was the most important local skin wettedness for input to the sensation of skin wetness ($r = 0.59$). The sweat absorbed in the clothing at the end of the experiment correlated well with the sensation of skin wetness at the end of the test ($r = 0.63$).

Sensation of sweating correlated best with esophageal temperature ($r = 0.59$); however, including average skin wettedness in the linear model increased the correlation considerably ($r = 0.68$), whereas skin temperature had no positive influence.

Thermal sensation of the body correlated well with esophageal temperature ($r = 0.57$), but even better with mean body temperature ($r = 0.59$). The correlation between thermal sensation of the body and mean skin temperature was significant, but not high ($r = 0.33$). Thermal sensation of the hands was far better correlated with core temperature ($r = 0.50$) than with hand skin temperature ($r = 0.26$).

The correlation between sensation of clothing temperature and the mean surface temperature of the underwear was significant, but not high ($r = 0.30$). A stronger correlation was found to esophageal temperature ($r = 0.44$), and including both esophageal and mean skin temperature in a linear model increased the correlation coefficient ($r = 0.55$).

The ambient temperature preference correlated best with esophageal temperature ($r = 0.35$). Including mean skin temperature in the model did not further increase the correlation coefficient.

4. Discussion

The set of rating scales used in this study was developed in order to give information separately about the thermal state of the body, of the sensation of temperature and wetness of the skin, the sensed temperature and wetness of the clothing in contact with the skin, and finally the ambient temperature preference. Alternate work/rest had a significant influence on all the subjective temperature sensations, whereas the influence of knit structure was less pronounced and only the sensed wetness of the clothing differed significantly between knit structures throughout the test.

Correlations between the subjective temperature ratings and the physiological responses for most of the various subjective ratings showed a high correlation with esophageal temperature. The sensation of skin wetness and sensed wetness of the clothing did not show such a correlation. All subjective temperature sensations were quite insensitive to knit structure, whereas alternate exercise/rest had a significant effect. Core temperature has in several studies been shown to be a major determinant (80–90%) of whole body thermal sensation, with mean skin temperature as another, but less important determinant (e.g., Bleichert *et al.*, 1973, Nielsen and Nielsen 1984). Exercise has a major influence on the core temperature level (Nielsen 1938, Saltin and Hermansen 1966), and therefore it is not surprising that we also observed significant changes in the thermal sensation resulting from changes in esophageal temperature induced by alternating work/rest (figure 3). Knit structure of the underwear only influenced the thermoregulatory responses at the skin. Skin temperature had a minor, but significant influence on the thermal sensation of the body in the present study; however, this must be due to variations of skin temperature with alternate work/rest during the course of time, as the difference in mean skin temperature caused by wearing various knit structures did not give rise to any difference in thermal sensation of the body at 9 min, 19 min, etc. Sensations of clothing temperature and ambient

temperature preference were not correlated to mean skin temperature. Although core temperature was the major determinant of these two experiences, the correlation coefficient was lower the further away from the core the evaluation was done. This may either reflect different buffer actions of the various underwear systems used, or that the influence of the environment is less than the influence of work/rest on these sensations, or that the distribution of the data is too narrow to get a good correlation. However, the intercorrelation between thermal sensation of the body (TSB) and sensation of sweating/shivering (SSS), clothing temperature (SCT) and ambient temperature preference (ATP), respectively, was high (TSB vs SSS: $r=0.81$; TSB vs SCT: $r=0.74$; TSB vs ATP: $r=0.71$).

For all three sensations of humidity in the skin environment, skin wettedness was an important factor; however, for the sensation of sweating esophageal temperature was more important. Core temperature is the most important afferent input to the temperature regulation which promoted sweating (Kerslake 1972), and seemingly core temperature also correlates well with the sensation of sweating with skin wettedness being another albeit less prominent determinant. Rated wetness of the clothing and wetness of the skin were the two sensations most sensible to the variation in knit structure of the underwear and to the difference in skin wettedness between the repeated work/rest periods. Both sensations correlated well with average skin wettedness, i.e., a physiological variable within the skin-clothing interface where the knit structure influenced the physiological responses. The sensation of wetness of the clothing was probably also influenced by the amount of sweat accumulated in the clothing; however, we could not measure this continuously throughout the test, only at the end of the test, and at this point in time the amount of sweat accumulated in the clothing correlated well with the sensation of wetness of the clothing. The present results indicate that subjective sensations of humidity at the skin and in the clothing are the most effective ratings to discriminate between clothing systems that do not differentiate enough in terms of insulation to provoke differences in core temperature.

How can we sense wetness on the skin and in the clothing without humidity sensors in the skin? Does sweat/water on the skin influence the thermoreceptors, so we sense a slightly different temperature with sweat/water on the skin compared to air? Or does the sweat/water on the skin contemporarily change the afferent input from thermoreceptors and tactile receptors in the skin, so that afferent input to the brain centres by experience is combined and connected to a sensation of skin wetness? Green (1980) showed that a tactile stimulus adopts thermal sensations from adjacent conductive thermal stimuli focusing thermal sensations at the site of tactile stimulation. Other investigators (e.g., Hensel and Zotterman 1951, Iggo 1960, Knisbestöl and Vallbo 1970, Poulos and Lende 1970) have shown that many mechanoreceptive afferents show significant increases in spontaneous firing rates as the skin is cooled, which may be perceived as an increment in tactile sensation at the skin. Warming the skin leaves most tactile afferents unaffected, except maybe for the polymodal nociceptors (unmyelinated C fibres) especially found in hairy skin (Torebjörk 1974). This means that a bimodal interaction actually binds tactile and thermal sensations together into a cohesive perception. In nude man a sweat/temperature-mediated increase in firing rate from the tactile receptors could be caused by a weight action of sweat on hair pressing these towards the skin. It would probably require a considerable skin wettedness before such a relatively light tactile stimulation could be sensed. In nude man the sensation of skin wetness is hypothesized to be more sensitive with a cool skin compared to a warm skin considering the temperature-mediated increase in

nervous firing rate. In the present study, this is supported by skin wettedness on the chest being the most important local input of the sensation of wetness (the cooling of the skin was greatest here). We are not aware of any studies on nude man relating skin wettedness directly to the sensation of skin wetness. Actually, few studies have been done on the sensation of skin wetness. However, Gagge *et al.* (1969) related skin wettedness to a sensation of discomfort. Discomfort was observed at 50.65% skin wettedness, which is a much higher value than observed in dressed man. Unfortunately, in this study we did not include experience of comfort in the ballots.

Clothing will move across the skin and stimulate cutaneous tactile receptors in proportion to the amount of skin displacement occurring upon contact with the fabric. Sweat (Naylor 1955, Gwosdow *et al.* 1986) and water externally applied to the skin surface (Nacht *et al.* 1981, Sulzberger *et al.* 1966) increase skin surface friction. The higher the friction, the larger the amount of skin displacement, and thus the greater the tactile stimulation. At the same time as movement of clothing produces tactile sensations it may also shortly produce stimulations with a different temperature. In the present study clothing temperature was experienced to vary with work:rest and with knit structure. An influence from heavy wet clothing on tactile receptors in the skin would give a stronger stimulus compared to sweat on nude skin, which indicates that in clothed man the threshold for sensation of wetness would be at a lower level of skin wettedness than in nude man. The lower the skin or the clothing temperature, the lower the level of skin wettedness that can be sensed. In a situation where the skin clothing interface is wet for an extended period of time hydration of the skin may occur. This swelling of the cells in the skin may sensitize the tactile receptors in the skin, and thus further increase the sensitivity to skin wetness. In the present study, this may have occurred in the EX2-RE2.

Comfort acceptance of garments next to the skin is in some way related to the ability of these garments to remove sweat from the skin clothing interface (Hollies 1977). It was proposed elsewhere (Nielsen and Endrusick 1989) that the openness of the knit structure in underwear allows for different degrees of convective cooling of the skin, thus producing different thermoregulatory responses at the skin. Results of Hock (1944) indicate that the extent of contact between underwear and skin may also be of direct importance for the thermoregulatory and the subjective responses. He found for mostly hydrophobic textiles that the sensation of chilling produced on the forearm by wet textile samples was related to the produced drop in skin temperature, which further was a function of the extent of contact the textile samples made with the skin. The extent of contact a fabric makes with the skin depends on the knit structure. However, the extent of contact with the skin also varies with the amount of absorbed humidity (Hock 1944). The hydrophilic materials used in the underwear in the present study did not absorb much sweat, and the heat loss by conduction due to the contact between the fabric and the skin can be considered negligible. The extent of contact between skin and underwear are probably of less importance with hydrophilic compared to hydrophobic materials. Fabrics which are superior in comfort at one moisture percentage usually show similar characteristics at other moisture levels (Hock 1944).

5. Conclusions

In summary, alternate work/rest significantly influenced various subjective temperature and humidity sensations. Knit structure of underwear influenced sensations of humidity significantly, but not sensations of temperature. The various sensations of

temperature mainly depended on core temperature, whereas the sensations of humidity correlated best with skin wettedness. It is therefore concluded, that subjective sensations of wetness of the skin and of the clothing are the best subjective tools to discriminate between the thermal function of garments that do not differ enough to produce differences in core temperature.

Acknowledgements

The experimental part of this work was done while Ruth Nielsen held a National Research Council-USARIEM Research Associateship. Drs R. R. Gonzalez and K. B. Pandolf are acknowledged for their review of the manuscript. In addition, the authors thank the Technical University of Denmark for use of their thermal manikin, and express their appreciation to the volunteers whose participation made this study possible.

The views, opinions, and or findings in this report are those of the authors and should not be construed as official Department of the Army position, policy, or decision, unless so designated by other official documentation. Human subjects participated in these studies after giving their free and informed voluntary consent. Investigators adhered to AR 70-25 and USAMRDC Regulation 70-25 on the Use of Volunteers in Research.

References

ASTM D1518-77 1977. Thermal transmittance of textile materials between guarded hot plate and cool atmosphere.

ASTM D1774-64 1964. Standard test method for measuring thickness of textile materials.

BERGLUND, L. G., CUNNINGHAM, D. J. and STOLWIJK, J. A. J. 1983. The resistance type dew point sensor for moisture measurements on sweating humans, in *Proceedings of the 6th Conference on Biometeorology and Aerobiology* (American Meteorological Society: Boston), 6-9.

BEECHER, A., BEEHING, K., SCARPERI, M. and SCARPERI, S. 1973. Thermoregulatory behaviour of man during rest and exercise. *Pflügers Archiv*, **338**, 303-312.

CRAWSHAW, I. I., NADIL, F. R., STOLWIJK, J. A. J. and STAMFORD, B. A. 1975. Effect of local cooling on sweating rate and cold sensation. *Pflügers Archiv*, **354**, 19-27.

DIN 54101 1984. Measurement of stationary thermal and water vapour resistance by means of a thermoregulatory model of human skin.

GAGGI, A. P. and NISHI, Y. 1977. Heat exchange between human skin surface and thermal environment, in D. H. K. Lee (ed) *Handbook of Physiology* (Bethesda), chapter 9. Waverly Press, Baltimore, pp. 69-92.

GAGGI, A. P., STOLWIJK, J. A. J. and HARDY, J. D. 1969. Comfort and thermal sensations and associated physiological responses at various ambient temperatures. *Environmental Research*, **2**, 209-229.

GREEN, B. G. 1980. Thermo tactile interactions: effects of touch on thermal localization, in D. Kenshalo (ed) *Sensory Functions of the Skin of Humans* (Plenum Press: New York) 223-240.

GWOSDOW, A. R., STEVENS, J. C., BERGLUND, L. G. and STOLWIJK, J. A. J. 1986. Skin friction and fabric sensations in neutral and warm environments. *Textile Research Journal*, **56**, 574-580.

HARDY, J. D. and DU BOIS, F. F. 1938. Basal metabolism, radiation, convection, and vaporization at temperatures of 22 to 35°C. *Journal of Nutrition*, **15**, 477-497.

HESSEL, H. and ZOTTERMAN, Y. 1951. The response of mechanoreceptors to thermal stimulation. *Journal of Physiology*, **115**, 16-24.

HOCK, C. W. 1944. Thermal properties of moist fabrics. *Journal of Research of the National Bureau of Standards*, **32**, 229-252.

HOLLIES, N. R. S. 1965, Investigation of the factors influencing comfort in cotton apparel fabrics, Contract 12-14-100-7183(72), US Dept. of Agriculture, New Orleans. [Referenced in Hollies *et al.* 1979.]

HOLLIES, N. R. S. 1977, Psychological scaling in comfort assessment, in N. R. S. Hollies and R. F. Goldman (eds.) *Clothing Comfort* (Ann Arbor Science Publishers: Ann Arbor) 107-120.

HOLLIES, N. R. S., CUSTER, A. C., MORIN, C. J. and HOWARD, M. E. 1979, A human perception analysis approach to clothing comfort, *Textile Research Journal*, **49**, 557-564.

IGGO, A. 1960, Cutaneous mechanoreceptors with afferent C fibres, *Journal of Physiology*, **152**, 337-353.

KERSLAKE, D. M. 1972, *The Stress of Hot Environments* (University Press: Cambridge).

KNISBESTÖL, M. and VALLBO, A. B. 1970, Single unit analysis of mechanoreceptor activity from the human glabrous skin, *Acta Physiologica Scandinavica*, **80**, 178-195.

MADSEN, T. L. 1971, A new instrument for measuring thermal comfort, in Salmark, H. (ed.), *Proceedings of the Fifth International Congress for Heating, Ventilating, and Air Conditioning*, Polyteknisk Forlag, Copenhagen.

NACHT, S., CLOSE, J. A., YEUNG, D. and GANS, E. H. 1981, Skin friction coefficient: changes induced by skin hydration and emollient application and correlation with perceived skin feel, *Journal of the Society of Cosmetic Chemists*, **32**, 55-65.

NAYLOR, P. F. D. 1955, The skin surface and friction, *British Journal of Dermatology*, **67**, 239-248.

NIELSEN, M. 1938, Die Regulation der Körpertemperatur bei Muskelarbeit, *Skandinavische Archives für Physiologie*, **79**, 193-230.

NIELSEN, R. and NIELSEN, B. 1984, Influence of skin temperature distribution on thermal sensation in a cool environment, *European Journal of Applied Physiology*, **53**, 225-230.

NIELSEN, R. and ENDRUSICK, T. L. 1990, Knit structure of underwear influences thermoregulatory responses to intermittent exercise, *European Journal of Applied Physiology*, **60**, 15-25.

NIELSEN, R., BERGUND, L. G., GWOSDOW, A. R. and DUBOIS, A. B. 1987, Thermal sensation of the body as influenced by the thermal microclimate in a face mask, *Ergonomics*, **30**, 1689-1703.

POULOS, D. A. and LENDE, R. A. 1970, Response of trigeminal ganglion neurons to thermal stimulation of oral-facial regions. I. Steady-state response, *Journal of Neurophysiology*, **33**, 508-517.

SALTMAN, B. and HERMANSEN, L. 1966, Esophageal, rectal and muscle temperature during exercise, *Journal of Applied Physiology*, **21**, 1757-1762.

SAS 1982, *Users Guide: Statistics*.

SULLIVAN, A. H. 1927, The cutaneous perceptions of softness and hardness, *Journal of Experimental Psychology*, **10** (6), 447-462.

SULZBERGER, M. B., CORTESE, T. A., FISHMAN, L. and WILEY, H. S. 1966, Studies of blisters produced by friction, *Journal of Investigatory Dermatology*, **47**, 456-465.

TØREBJØRK, H. E. 1974, Afferent C units responding to mechanical, thermal, and chemical stimuli in human non-glabrous skin, *Acta Physiologica Scandinavica*, **92**, 374-390.

UMBACH, K. H. 1982, Beeinflussung des Tragekomforts von Kleidung durch lokale Wärme- und Feuchtestaus, *Hohensteiner Forschungsbericht*, Mai, 1-10.

WINSLOW, C.-E. A., HERRINGTON, L. P. and GAGGE, A. P. 1937, Relations between atmospheric conditions, physiological reactions and sensations of pleasantness, *American Journal of Hygiene*, **26**, 103-115.

Manuscript received 2 October 1989.
Manuscript accepted 11 January 1990.

